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Interdependencies between Energy and Transportation Systems for National Long Term Planning

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Abstract

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Disciplines

Power and Energy | Sustainability | Systems Engineering | Transportation Engineering

Comments

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Interdependencies between Energy and Transportation Systems for National Long Term Planning

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Abstract The most significant energy consuming infrastructures and the greatest contributors to greenhouse gases for any nation today are electric and freight/passenger transportation systems. Technological alternatives for producing, transporting, and converting energy for electric and transportation systems are numerous. Addressing costs, sustainability, and resiliency of electric and transportation needs requires long-term assessment since these capital-intensive infrastructures take years to build with lifetimes approaching a century. Yet, the advent of electrically driven transportation, including cars, trucks, and trains, creates potential interdependencies between the two infrastructures that may be both problematic and beneficial. We are developing modeling capability to perform long-term electric and transportation infrastructure design at a national level, accounting for their interdependencies. The approach combines network flow modeling with a multiobjective solution method. We describe and compare it to the state-of-the-art in energy planning models. An example is presented to illustrate important features of this new approach.

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1 Introduction

Most US energy usage is for electricity production and vehicle transportation, two interdependent infrastructures. The strength and number of these interdependencies will increase rapidly as hybrid electric transportation systems, including plug-in hybrid electric vehicles and hybrid electric trains, become more prominent. There are several new energy supply technologies reaching maturity, accelerated by public concern over global warming. US DOE-EIA [1] suggests that national expenditures on electric energy and transportation fuels over the next 20 years will exceed $14 trillion, four times the 2010 federal budget [2]. Intentional and strategic energy system design at the national level will have very large economic impact.

The proposed work is motivated by a recognition that tools, knowledge, and perspective are lacking to design a national system integrating energy and transportation infrastructures while accounting for interdependencies between them, new energy supply technologies, sustainability, and resiliency. Our goal is to identify optimal infrastructure designs in terms of future power generation technologies, energy transport and storage, and hybrid-electric transportation systems, with balance in sustainability, costs, and resiliency. We will characterize interdependencies between energy resource portfolio and energy/vehicular transportation systems at the national level.

This chapter begins with an overall description of our approach in section 2, including the underlying models for the energy and transportation sectors. In section 3 we identify the most relevant interdependencies that an integrated energy and transportation system could present. The goal of our approach is to identify a set of optimal solutions in terms of competing objectives (cost, sustainability and resiliency), which are defined in section 4. A review of the state-of-the-art in infrastructure planning software and methodologies follows in section 5; leading to the formulation of our approach in section 6. That formulation is applied to a small test system in section 7 and the chapter is then concluded with a discussion in section 8.

2 Modeling approach

The energy system is comprised of (but not limited to) electricity, natural gas, liquid fuels, nuclear, biomass, hydroelectric, wind, solar, and geothermal resources. Modeling of national freight and passenger transportation focuses on state-to-state travel; we consider both infrastructures (rail, highways, locks/dams, roads, ports, airports) and fleets (trains, barges, trucks, personal vehicles, airplanes, etc.), and there may be different kinds of fleets for each mode (e.g., diesel trains and electric trains or conventional and plug-in hybrid electric).

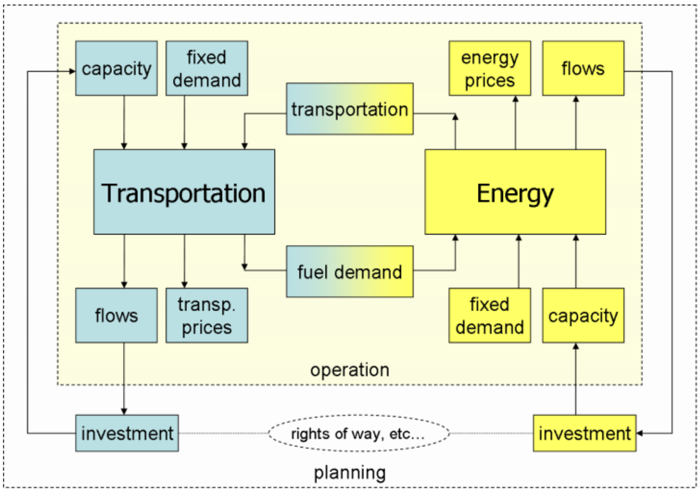

Fig. 1. Proposed model that integrates the energy and transportation systems at two levels: operation and planning.

Fig. 1 captures the scope of our modeling effort. The transportation and energy systems interact mainly at two different stages: operation and investment. At the operational level each system needs to satisfy its demand with the existing capacity. However, operation of the two systems, and ultimately investment, are interdependent; while the transportation sector demands energy in the form of fuel, the energy sector requires the movement of raw bulk energy sources (e.g. coal or natural gas for thermal power plants). At the same time, the cost of meeting those reciprocal demands has an impact on final prices for energy and transportation. The ever-growing public need for energy and transportation creates the necessity to invest in new capacity. Given the potential for increased coupling between energy and transportation, it is apparent that better designs of both can be achieved if these designs are performed together.

2.1 Energy systems modeling

A generalized network flow transportation model [3,4] is used to model energy systems, where commodity flow is energy, and transportation paths are AC and DC electric transmission, gas pipelines (for natural gas and/or hydrogen), and liquid fuel pipelines (for petroleum-based fuels, biofuels such as ethanol or biodiesel, and anhydrous ammonia). Energy transport by rail, barge, and truck is included in the freight transport model.

Each source node, specified with location, is connected to a fictitious source node that supplies all energy. Arcs emanating from each source are characterized by maximum extraction rate (MBtu/month) and extraction cost ($/MBtu/month).

Petroleum, coal, natural gas, and uranium have finite capacities, while renewables have infinite capacities. All sources have finite maximum extraction rates. Conversion and transportation are endowed with: capacity (MBtu-capacity/month), efficiency (%), operational cost ($/MBtu-flow/month), investment cost ($/MBtu-capacity/month), component sustainability metrics (e.g., CO_2 tons/MBtu-flow), and component resiliency (e.g., reliability).

2.2 Transportation systems modeling

The freight transport system is modeled as a multi-commodity flow network where the flows are in the units of tons of each major commodity. A commodity is major if its transportation requirements comprise at least 2% of the nation's total freight ton-miles. Data available to make this determination [5] indicates this criterion includes 23 commodities that comprise 90% of total ton-miles (e.g., the top eight, comprising 55%, are in descending order: coal, cereal grains, foodstuffs, gasoline and aviation fuel, chemicals, gravel, wood products, and base metals).

There are two fundamental differences between this formulation and that of the energy formulation. Whereas the energy formulation must restrict energy flows of specific forms to particular networks (for example, natural gas or hydrogen cannot move through electric lines or liquid fuel lines), commodities may be transported over any of the transport modes (rail, barge, truck). Also whereas energy movement requires only infrastructure (electric lines, liquid fuel pipelines, gas pipelines), commodity movement requires infrastructure (rail, locks/dams, roads, ports) and fleet (trains, barges, trucks), and there may be different kinds of fleets for each mode (e.g., diesel trains or electric trains).

To accommodate these differences, the transportation formulation is comprised of two multi-commodity flows [6], one embedded inside the other. Commodities flow through the network formed by the different types of fleet available. At the same time, the units in those fleets travel along the network formed by the different infrastructures. An effective method to convert this situation into an ordinary network problem is captured in Fig. 2, where the flow from node A to node B is divided according to the types of infrastructures first and then into the different types of available fleets. Then one can apply capacity limits to the appropriate fictitious arcs.

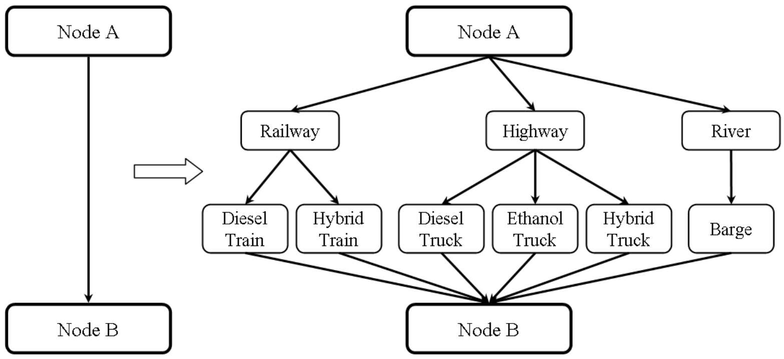

Fig. 2.. Decomposition of transportation arc in two steps: infrastructure and fleet.

3 Interdependencies

The described model enables analysis of interdependencies between resource mix, sustainability, cost and resiliency at a national level, and we intend to study these relationships under various assumptions of technological maturity (cost, efficiency, reliability) for wind, solar, hydrogen, nuclear, geothermal, gasification, biofuel production, and hybrid electric transportation systems (plug-in hybrid vehicles or hybrid trains).

The following interdependencies present special interest to us and can be studied within the broad scope of our model:

1. Wind and resource mix: Since wind is carbon-free, low-cost, and renewable, popular thought is to maximize its use; yet use of wind energy is constrained, since: (1) its night-time peak is in anti-phase with day-time electric load peak; (2) the uncertainty in its day-ahead availability increases costs associated with maintaining higher levels of reserve; (3) high-voltage transmission necessary to move it from wind-intensive regions to load centers is insufficient. We will investigate interdependencies between wind-supplied energy and three particular resource types: (a) PHEV, hybrid train via charging stations; (b) fuel cells via electrolysis to produce hydrogen; (c) hydro pumped storage.
2. Gasification, carbon, and transportation: Integrated gasification combined cycle (IGCC) units convert fossil fuels and/or biomass to syngas to fire a combined cycle unit. IGCCs obtain high efficiencies and enable effective carbon capture/sequestration. Although expensive to build and presently less reliable to operate, an IGCC plant provides a uniquely attractive degree of versatility via low-carbon use of fossil fuels and/or biomass, and co-production of electric energy, hydrogen, and diesel fuel.

3. Transportation patterns and resource mix: Existing highway and rail infrastructure was designed without consideration of coupling to bulk energy transport. We will use concepts from existing statewide [7] and metropolitan [8] travel demand models to refine our freight and energy models to study how passenger and freight transportation patterns are likely to change as a result of increased penetration of PHEV, hybrid trains, and biofuels, identifying interdependencies between electric grid operations/expansion, traffic operations (vehicle movements caused by daily/seasonal population shift cycles) and transportation network expansion.
4. Right-of-way (ROW) and resource mix: The Midwest US has 5 times as much potential wind capacity as present regional load, so moving large amounts of wind from the Midwest to load centers of the east and west coasts is under consideration [9,10]. Midwest-to-east coast alone requires crossing at least twelve states, each with regulatory oversight reflecting intense public sensitivity to overhead transmission. The relation to rail is intriguing. On the one hand, ROW could be obtained from converted rail routes made available by reduction in eastward coal transport caused by increased wind availability. On the other hand, large-scale deployment of hybrid trains may be facilitated by deploying overhead transmission in rail ROW while powering trains from that same overhead transmission.
5. Prices of petroleum, natural gas, and electricity: Significant price variability has occurred in each of these three forms of energy. Our model will provide locational marginal prices for any energy network-transportable energy form [3,4] via the dual variables to nodal balance constraints [11]. We will explore price interdependencies between these energy forms as affected by coupling resulting from hybrid electric transportation systems.
6. Demand coordination: Demand coordination offers significant opportunity to enhance sustainability and resiliency while decreasing costs. Microprocessor control of residential, commercial, and industrial loads, based on real-time prices, offers effective means of time-shifting demand, an approach PHEV-owners and hybrid train operators could use to make money by charging off-peak and supplying on-peak. Deployment of a high voltage transmission "national superhighway" [9,10] could enable spatial-temporal coordination, e.g., 11 am Southwest solar could be used to supply East-coast 2 pm peaks, or New York City PHEVs could sell 9 pm energy to Seattle residents for their 6 pm peak. Significant deployment of load-side, distributed solar and wind power resources could heavily reduce the need for centralized generation. PHEVs and hybrid trains, if coupled with high-efficiency engines, could increase their on-board power generation capacity, resulting in more on-peak electric capacity.
7. Appearance of new competition: The study of investment on new technologies can unveil the possible existence of parallel paths to satisfy the same demand in the energy system (e.g., coal plant vs. wind), the transportation system (e.g., rail vs. truck) or both (e.g., fuel transportation vs. electric transmission). These parallel paths could create opportunities for the development of new markets or even the combination of existing ones.

8. Environmental legislation: Pollutants and greenhouse gas emissions are byproducts of transportation use or energy processing operation, as well as construction of new infrastructure. Existing or forthcoming legislation can have a tremendous impact on the proposed portfolio for the energy and transportation systems. New policies can take the form of emission limits or “caps”, allowances assignment and trade or taxes per volume emitted.
9. Capacity investment: Freight system “chokepoints,” particularly ports, and energy system “bottlenecks,” particularly electric transmission systems, are continuous targets of improvements. We will investigate how improvements in one infrastructure affect demand, and the need for capacity, in the other.

To illustrate an emerging transformative interdependency between the energy and transportation infrastructures, which can potentially have a tremendous impact on the operation of both systems, consider PHEVs with vehicle-to-grid (V2G) capabilities [12,13]. The main concept behind the V2G technology is to allow vehicles to discharge their stored energy back to the power grid, by use of bi-directional power electronic dc/ac interfaces and communications protocols. PHEVs without V2G capability are “just” increased load on the power system, which must be nevertheless capable of supplying the additional power required to charge them (usually during the night, which is optimal from the perspective of the power grid operator [15]). However, if the V2G technology is further developed, standardized, and widely adopted, then a whole new range of exciting possibilities for power system operation arises. Recent studies have shown that V2G technology can help stabilize the grid during power shortages [15]. Some studies also suggest that PHEVs can be the key component that will permit the penetration of renewable resources to the power grid up to levels of 40–50% [16–18], currently limited by transmission, storage, and reliability considerations. In essence, PHEVs would function as a huge system-wide distributed energy storage element, which would be highly reliable, and would help mitigate the requirement for storing renewable energy locally at the point of generation.

4 Multiple Objectives

One of the core features of this approach is its multiobjective nature. The final objective is to find a Pareto front of non-dominated solutions. Rather than a predetermined hierarchy or weighted system before the optimization takes place, the trade-offs can be analyzed a posteriori, giving decision makers and general public a solid background to determine where their efforts should be focused on.

The objectives are grouped in three distinctive categories: cost, sustainability and resiliency, which are presented below.

4.1 Cost

There are two equally important components to the cost objective that can be differentiated: operational and investment costs. The impact of the latter can be usually perceived as more notorious given the amount of capital that requires over a relative short period of time. However, the operational component could have a bigger impact on the total cost and should definitely be handled with care.

Investment cost is calculated in dollars per unit of maximum flow increased in a period of time: MBtu-capacity for energy networks or Ton-capacity for transportation network. The concept of overnight cost is used, that is the cost of financing the entire construction of a given infrastructure if only one payment was going to be done at one point it time. Among other concepts, this cost would include materials, labor, financial costs, intellectual property, and dismantling costs. Salvage value would be taken into account with the appropriate inflation correction, should it exist.

Operational cost, as opposed to investment cost, is expressed in a dollar per unit of energy produced or unit of mass transported basis. It could include, but is not limited to, some of the following: labor (operators, drivers), maintenance, byproduct disposal (nuclear waste, ash), or non-fuel materials (e.g. limestone in fossil fuel plants). Useful byproducts could potentially reduce the overall operational cost. There are two traditional operational cost components that we don't assign directly: fuel costs and amortization of the investment. The first is taken care of in the representation of the fuel sources and distribution networks with the appropriate interconnections and the latter is included in the investment cost.

4.2 Sustainability

We view sustainability in terms of environmental impact and supply longevity. We capture four classes of environmental impacts related to energy and transportation systems: net emissions, nuclear waste, water consumption (e.g., for biofuel production), and resource displacement (e.g., land usage). The most relevant emissions that result from energy and transportation systems are the emissions of four air pollutants (CO, NO_x, SO_2 and volatile organic compounds) [19], and greenhouse gas emissions (CO_2 and methane) [20].

For each environmental impact belonging to any of our four classes (emissions, waste, consumption, displacement) a linear expression is considered. Coefficients representing the impact per unit of flow need to be determined prior to the optimization process. Environmental consequences of investment can also be included and computed by analyzing the nominal impact of the life cycle of each infrastructure, such as emission during the processing of raw materials (steel, concrete) or during construction.

We also characterize supply longevity for a depletable resource (e.g., coal, gas, uranium) as the remaining years for the resource if used at the average rate over the simulation time. Sustainability expressions for water and land as depletable resources or air pollutants that should not exceed a predetermined threshold can be modeled as *complicating constraints* [3] that specify flow relationships between several arcs. Dual variables for these constraints provide valuation of the corresponding metric in terms of its per-unit effect on objectives. These valuations can be linked to market prices as in the case of tradeable SO_2 allowances [21–23]. We will explore potential linkages with models reflecting natural capital [24] and applications to carbon cap and trade markets [25].

4.3 Resiliency

The resiliency of the system will be evaluated by studying the impact of fictitious arc failures or cost increases, representing possible contingencies on the different networks. Contingencies may be represented by a decrease in capacity and/or an increase in cost at one or multiple nodes, occurring at any point in time during the simulation span, and for different durations, ranging from a single time step to the complete study period.

Arc failure probabilities are a function of exposure to physical failure modes such as natural events (e.g., hurricanes, earthquakes, extreme heat, drought, flood), equipment failures (e.g., train derailments, pipeline explosions, bridge collapse, software/communication system failure), and terrorist acts. They also depend on exposure to sociological and political risk (e.g., another nation's ability to curtail exports to the U.S. or to demand higher energy prices). A uniquely important influence is the dependence of each arc's exposure to equipment failure that depends on workforce quantity and quality.

Although this part of the work is yet to be developed to its full extent, we envision several options to evaluate the resiliency of the energy and transportation systems. A straightforward approach to be employed within the optimization consists of computing the increase that contingencies cause in the system's operational cost [26], once an investment scheme has been determined. We also compute traditional network reliability indices for the system such as unavailability or expected energy not-supplied based on, for example, identification of minimum cut sets [27–31]. Since the system at this level is robust to bulk non-deliverability, a more sensitive resiliency metric may be appropriate, e.g., one that is based on energy price variation over time, computable within our model as the integration over time of locational marginal prices. A related metric, the cumulative reduced price [27], depends on price differences between two nodes summed over time. This metric, useful for ranking future investments, complements information obtained from the capacity part of the optimization solution.

The possible combination of causes produces a large space of contingencies, each with their own occurrence probability and very diverse potential impacts.

Finding the set of contingencies that represent the highest risk can be achieved with various techniques, such as sensitivity analysis on the operational solution, Monte Carlo simulations, or specialized explicit formulations [32]. This set depends on the structure of the energy and transportation networks, which depends on the profile of the investment decisions. Once the minimum-cost flow problem is solved for the selected contingencies, metrics can be obtained based on the average increase on the overall operational cost with respect to a reference case. Locational marginal prices and minimum cut sets can also be used during the optimization process or in the result analysis.

5 State-of-the-art and model attributes

We have performed a detailed comparison between the most advanced energy planning models, which include the National Energy Modeling System (NEMS) [33], the MARKAL/TIMES suite [34], and WASP-IV [36]. Modeling on the transportation side includes national freight forecasting models and tools [36,37] and statewide passenger travel forecasting models [7]. Transportation investment planning tools include (but not limited to) the Highway Economic Requirement System (HERS-ST) [38] for highway investments, and RailDec [39] for rail investments. Other related work includes designs for novel energy infrastructure systems [40–42], infrastructure interdependencies [43-48], and system-wide modeling of energy systems [49] including the EPA's Integrated Planning Model [50].

We concluded that our proposed work would provide the following attributes not currently available in any of these models:

1. Ability to optimize multiple objectives;
2. Use of resource depletability as a sustainability measure;
3. Availability of resiliency metrics;
4. Rigorous modeling of interactions between energy and freight/passenger transportation.

In addition, our proposed solution approach, which combines advanced network flow modeling, multiple decomposition techniques, and multiobjective solution methods with computation performed via high-performance computing, represents a unique integration of the very best in approach, algorithm, and computing platform in addressing an extreme-dimensionality problem of high technical, political, and social importance today.

6 General formulation

In this section, the formulation used to achieve the characteristics described above. The explanation of the formulation is preceded by an introduction to the nomenclature used.

6.1 Nomenclature

Sets and networks

N	Set of nodes
M	Set of arcs
T	Set of time periods
En	Set of energy networks
Tr	Set of transportation networks
Inf	Set of transportation infrastructures
Fleet	Set of transportation fleet
Efuel	Set of energy networks that provide fuel to transportation
TrEn	Set of transportation networks that provide fuel to generation nodes

Objective Functions

CostOp	Total cost of operating the energy and transportation networks
CostInv	Total investment cost
$Emissions_k$	Total emissions for pollutant k

Parameters

$H_{(i,j,l)}(t)$	Efficiency of arc (i,j) in network l, during time t
$lb_{(i,j,l)}(t)$	Lower bound for flow in arc (i,j) in network l, during time t
$Ub_{(i,j,l)}(t)$	Upper bound for flow in arc (i,j) in network l, during time t due to the initial existing infrastructure
$lbInv_{(i,j,l)}(t)$	Minimum allowed capacity increase in arc (i,j) in network l, at time t
$ubInv_{(i,j,l)}(t)$	Maximum allowed capacity increase in arc arc (i,j) in network l, at time t
$costOp_{(i,j,l)}(t)$	Operational cost for flow in arc (i,j) in network l, during time t
$costInv_{(i,j,l)}(t)$	Investment cost for capacity increase in arc (i,j) in network l, at time t
$kEm_{(i,j,l)}(t)$	Emission rate for pollutant k for flow in arc (i,j) in network l, during time t
$heatRate_{(i,j,E)}(t)$	Heat rate for thermal generation i at node j, during time t
$fuelCons_{(i,j,l)}(t)$	Fuel consumption for transportation mode i arriving at node j in network l, during time step t

$d_{(j,l)}(t)$	Fixed energy or transportation demand at node j in network l, during time t
r	Discount rate

Decision Variables

$f_{(i,j,l)}(t)$	Operational flow of arc (i,j) in network l, during time t
$capInv_{(i,j,l)}(t)$	Capacity increase due to investment in arc (i,j) in network l, during time t

6.2 Formulation description

The optimization problem associated with this model can be conceptually described by the optimization problem given in (1),

$$\begin{aligned}
&\mathbf{min}\left\{CostOp + CostInv,\ Emissions_k\right\} \\
&\mathbf{subject\ to:} \\
&\mathit{Meet\ energy\ demand}, \qquad\qquad (1) \\
&\mathit{Meet\ transportation\ demand} \\
&\mathbf{Decision\ Variables:}\ \mathit{flows,\ capInv}
\end{aligned}$$

There are two objectives (cost and emissions), each having an energy and a transportation component. We minimize these objectives under constraints of meeting demands on energy, and freight transport. Decision variables characterize operations (*flows*) and capacity investments (*capInv*).

The following formulation (2) corresponds to a first approach to the modeling capabilities that have been previously described in this chapter. Each arc is specified by (i,j,l), where i is the origin node, j is the terminal node and l is the network to which it belongs.

A key attribute of this model is that networks of different energy and transportation forms are represented separately, linked only to the extent that the energy form of one network can be converted to the energy form of another. The simulation period is specified by T.

Objectives (2a) are to minimize operational (2g) and investment (2h) costs, and pollutant emissions (2i), subject to the energy and transport balance constraints (2b) for all nodes and the flow bound constraints for all arcs (2c, 2e).

Flow balance at the nodes is enforced by (2b), where the right-hand-side represents demand on the commodity form at node j. Certain energy nodes can have a freight-related demand (2k) to fuel the need for transportation. At the same time, the demand of energy related commodities in some given transport networks (carbon, natural gas) will depend on the generation rate at those nodes (2j). The efficiency parameter $\eta_{(j,k,l)}$ in (2b) accounts for losses in the energy network, and equals 1 in the transport system since it is assumed to be lossless.

$$\mathbf{min}\left\{CostOp + CostInv, Emissions_k\right\}(2a)$$

subject to :

$$\sum_k \eta_{(j,k,l)} f_{(j,k,l)}(t) - \sum_i f_{(i,j,l)}(t) = d_{(j,l)}(t), \qquad \forall j \in N, \forall l \in \{En,Tr\}, \forall t \in T \qquad (2b)$$

$$lb_{(i,j,l)}(t) \le f_{(i,j,l)}(t) \le ub_{(i,j,l)}(t) + \sum_{z=0}^{t} capInv_{(i,j,l)}(z), \quad \forall (i,j) \in M, \forall l \in \{En\}, \forall t \in T \qquad (2c)$$

$$lbInv_{(i,j,l)}(t) \le capInv_{(i,j,l)}(t) \le ubInv_{(i,j,l)}(t), \qquad \forall (i,j) \in M', \forall l \in \{En\}, \forall t \in T \qquad (2d)$$

$$lb_{(i,j,l)}(t) \le \sum_{l \in Tr} f_{(i,j,l)}(t) \le ub_{(i,j,l)}(t) + \sum_{z=0}^{t} capInv_{(i,j,l)}(z), \forall i \in \{Inf, Fleet\}, \forall l \in \{Tr\}, \forall t \in T \qquad (2e)$$

$$lbInv_{(i,j,l)}(t) \le capInv_{(i,j,l)}(t) \le ubInv_{(i,j,l)}(t), \qquad \forall i \in \{Inf, Fleet\}, \forall j \in M', \forall l \in \{Tr\}, \forall t \in T \quad (2f)$$

where :

$$CostOp = \sum_{t \in T} \sum_{(i,j,l) \in M} (1+r)^{-t} costOp_{(i,j,l)}(t) f_{(i,j,l)}(t) \qquad (2g)$$

$$CostInv = \sum_{t \in T} \sum_{(i,j,l) \in M'} (1+r)^{-t} costInv_{(i,j,l)}(t) capInv_{(i,j,l)}(t) \qquad (2h)$$

$$Emissions_k = \sum_{t \in T} \sum_{(i,j,l) \in M} kEm_{(i,j,l)}(t) f_{(i,j,l)}(t) \qquad (2i)$$

$$d_{(j,TrEn)}(t) = \sum_i heatRate_{(i,j,l)}(t) f_{(i,j,l)}(t), \qquad \forall j \in N_{TrEn}, \forall t \in, \forall t \in T \qquad (2j)$$

$$d_{(j,Efuel)}(t) = \sum_{\substack{\forall l \in \\ \{Tr\}}} \sum_{\substack{i \in \\ \{Fleet\}}} fuelCons_{(i,j,l)}(t) f_{(i,j,l)}(t), \qquad \forall j \in N_{Efuel}, \forall t \in T \qquad (2k)$$

Decision Variables : $\quad f_{(i,j,l)}(t), capInv_{(i,j,l)}(t) \ge 0$

Upper capacity bounds in (2c, 2e) may change due to the presence of decision variables $capInc_{(i,j,l)}(t)$, modeling facility expansion, which can be constrained (2d, 2f) to represent minimum and maximum levels of investment. In energy networks, every arc is constrained independently. However, in the transportation networks the upper bound and capacity investment is assigned to the combination of commodity flows transported from a determined pair of nodes by a mode of transportation (infrastructure of fleet).

Cost expressions (2g) and (2h) are expressed as present worth using present worth factor $(1+r)^{-t}$. Operational costs in (2g) are summed over the entire arc set M, but investment costs in (2h) are summed over a specified set M' which enables consideration of both connected and unconnected nodes while controlling problem dimensionality. Salvage values are taken into consideration when the effective life of the investment exceeds the end of the simulation time [51].

Pollutant emissions (2i) are calculated using the amount of pollutant emitted per unit of energy flow, $kEm_{(i,j,l)}(t)$. The flows that are assigned an emission rate different than zero are thermal generation units and transportation flows.

7 Numerical example

To illustrate some of the capabilities of the proposed model a simple example with two geographical regions has been created and analyzed based on a previous model [52] that only took the energy system into consideration.

7.1 Description

The illustrated example (Fig. 3) features a high level representation of the energy and transport relations between the Midwestern and Eastern sections of the United States. These areas are also respectively referred to as “1” and “2”. We consider the Midwest region to be delimited by the states between North Dakota, Wisconsin, Mississippi and Texas.

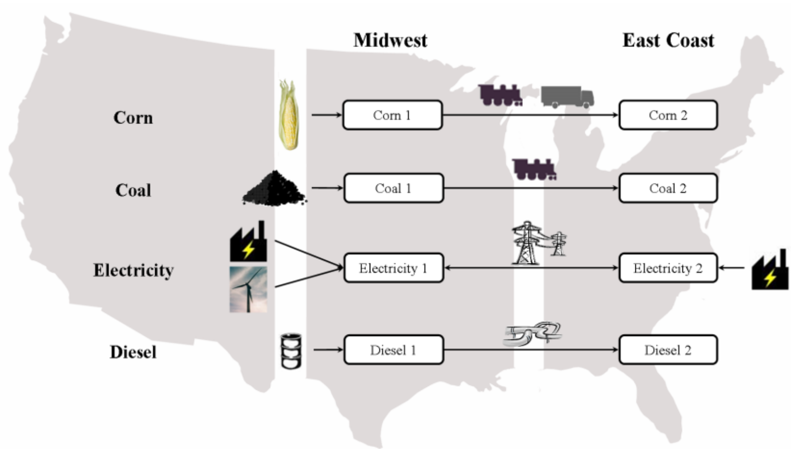

Fig. 3. Proposed example layout displaying the two geographical regions (East Coast and Midwest), and the different energy and transportation layers.

The Midwestern area is assumed to produce two types of commodities, coal and corn, which need to be transported to meet the East Coast demand. To simplify the model, it is assumed that coal is produced in the Illinois Basin with enough capacity to meet the thermal generation demand in the East Coast and the Midwest. To transport these commodities, two different infrastructures, railway and highway, can be utilized. Only one type of fleet is accounted for in each infrastructure, train and truck, respectively.

Two different energy networks are considered. The diesel network is fed by the production in the Midwest and its mission is to fulfill the need for fuel from trains and trucks. Electricity supply constitutes the second energy network. Both areas can produce electricity from thermal plants, which drive the demand for coal on the transportation side, and are connected by high-voltage power lines to allow energy trading. The Midwestern area has potential to use wind as a source for electricity, although there is no capacity installed at the beginning of the planning period, which lasts 40 years.

In order to capture all the components of the formulation, the previous set of physical nodes and arcs can be expanded as shown in Fig. 4. Note that columns represent the four networks and every row represents a node, corresponding to a physical region.

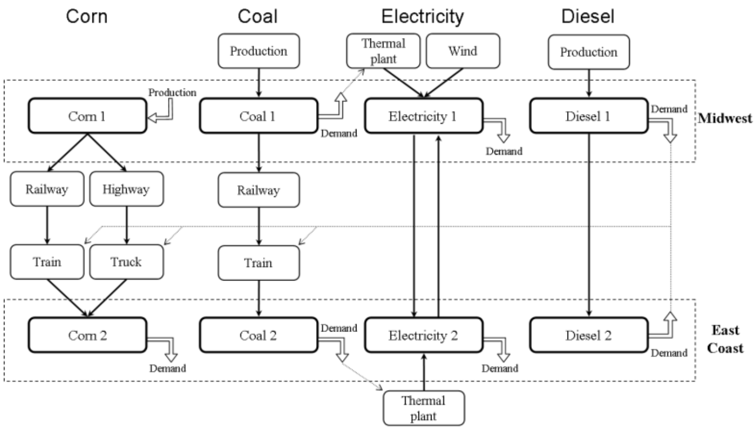

Fig. 4. Example node and arc expansion for the two-node example. The two physical nodes are displayed horizontally, while the different networks are laid out vertically. Solid arrows represent flows and dashed arrows represent interconnection between networks.

In the transportation networks, fictitious nodes have been added in between the physical regions to represent the different alternatives of conducting the flow between the Midwest and the East Coast. The transmission line in the electric network is replaced by two opposite directional arcs to ensure the non-negativity of the flows [3]. The dashed lines represent the increase in demand on a node due to activity on other network, i.e. thermal units increase the demand for coal and the use of train and truck for transportation drive the demand for diesel.

To simplify the analysis we assume that there will only be capacity limits and investment in the following parts of the system: train and truck transportation, thermal plants, wind generation and electricity transmission. No investment on infrastructure in considered. Also, there is no retirement of facilities or infrastructure so the initial capacity is assumed to be available throughout the simulation.

7.2 Parameters

The simulation is performed for 40 years with a time step of a year. A more refined model would use shorter monthly time steps, as suggested in section II, in order to obtain more accurate results. Operational and investment parameters for energy networks are summarized in Table 1, while Table 2 contains the appropriate parameters of capacity, frequency of travel, costs and emissions for the available fleet. Data for this model has been collected from [53–58].

Table 1. Electricity network parameters

	Coal fired	Wind	Transmission
Initial capacity	225 / 180 GW	0 GW	50 GW
Max. investment	10 GW/year	3.5 GW/year	5 MW/year
Op. cost	1.7 $/MWh	7 $/MWh	2 $/MWh
Investment cost	2.12 $/MW	1.65 $/MW	825 $/kW-mile
Efficiency	9.95 MMBtu/MWh	35 %	100 %
CO_2 emission rate	55.77 lb/MWh	0	

Table 2. Transportation parameters

	Train	Truck
Capacity	3200 ton/load	26 ton/load
Loads/year	68 loads	104 loads
Initial capacity	3500 trains	100,000 trucks
Operational cost	0.05 $/ton mile	0.16 $/ton mile
Fuel use	341 Btu/ton mile	3357 Btu/ton mile
CO_2 emission rate	0.2 lb/ton-mile	0.6 lb/ton-mile
Max. investment	50 trains	100 trucks
Investment cost	31 million $/train	200,000 $/truck

The electric demand is set to 141 GW for the Midwest region and 118 GW for the East Coast, with a growth of 1.5% every year. The amount of corn shipped from the Midwest to the East Coast equal 300 million tons, with a 0.5% yearly growth. The average distance between the two regions is set to 750 miles. Coal is produced in the Illinois Basin with a content of energy equal to 11,800 Btu/short ton and a cost of $85 per short ton.

All costs are subject to a constant inflation of 2%, and a constant discount rate of 7% is used in the economic analysis. Salvage values are assigned for the investments close to the end of the simulation period. All investments are set to devaluate linearly for a period of 15 years.

7.3 Base case results

The formulation is implemented using Matlab and solved using version 10 of CPLEX. It consists of 914 variables and 1074 constraints. Solution time is under a second, running on a 3.6 GHz Pentium 4 processor with 2 GB of RAM. Table 3 contains a summary of the optimum investment portfolio obtained.

Table 3. Cost and investment results

	Cost	Investment
TOTAL	2.19 trillion $	-
Operational	2.06 trillion $	-
Investment	125.83 billion $	-
- Coal Midwest	11.40 billion $	68.17 GW
- Transmission	4.87 billion $	38.95 GW
- Wind	90.70 billion $	136.50 GW
- Train	18.87 billion $	1244 trains

As we mentioned at the beginning of the chapter US DOE-EIA estimates [1] that the national cost of electric energy and transportation fuels over the next 20 years around $14 trillion. The estimate given by the model is very reasonable, taking into account that we used a very high level representation and only a small part of the transportation and energy systems.

Investments take place progressively at different moments in time for different arcs. Transmission capacity is added mainly in the first seven years, while new coal generation capacity in the Midwest is constructed between years eight and forty. Investment on new wind capacity is constant and equal to the maximum over the whole simulation period. Finally, investment on trains happens during the last 25 year period. During the 40 years of the study, CO_2 emissions are estimated to be 33.7 billion tons. Fig. 5 represents the generation mix forecasted for the simulation period.

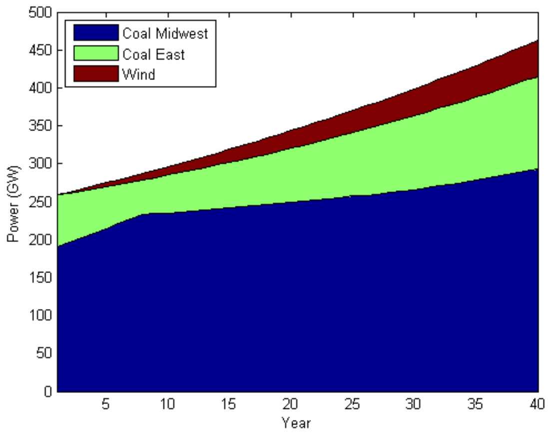

Fig. 5. Electricity generation for the base case

The model is also capable of forecasting electricity prices (Fig. 6). Energy in the Midwest is always cheaper than in the East Coast since it does not require the use of transmission or transportation. The price difference is relatively small between years 26 and 33 because the electric transmission line is not congested in that period of time. The separation is more noticeable in years 1, 2 and 26 to 40 due to congestion in the transportation side. Coal and corn utilize all train capacity, and part of the corn has to be delivered by truck, rising transportation costs.

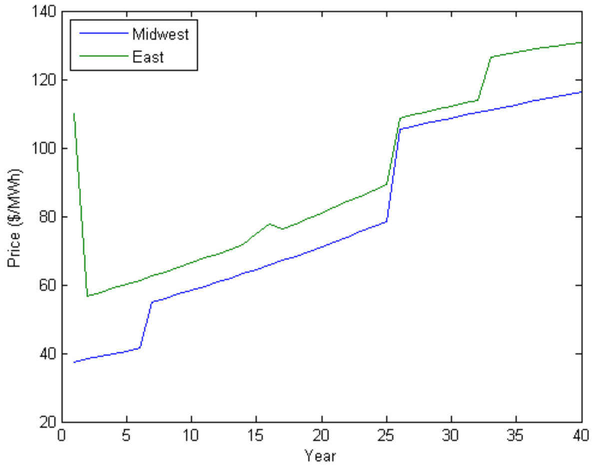

Fig. 6. Evolution of electricity prices for the two geographical nodes

7.4 Multiobjective results

Now let us assume that, in order to improve the system's frequency regulation and load following, investments on wind are required to be associated with some sort of electricity storage, doubling the cost of wind investment. In this case, wind energy is not economical anymore and any solution that seeks a reduction on CO_2 emissions by switching coal to wind will incur a higher cost. In this case, cost and emissions are two competing objective functions. By forcing different levels of investment on wind, we can find the trade off between the two objectives (Fig. 7).

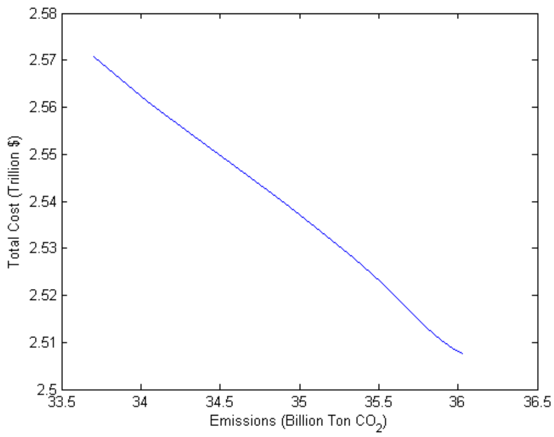

Fig. 7. Front of solutions two analyze the trade-off between emissions and total cost

A very simple metric to evaluate the reliability of the electric system is the reserve margin, the relative difference between installed thermal generation capacity and demand. The smaller the margin, the more probable that demand cannot be met due to unforeseen loss of generation. Adding the corresponding constraints to the formulation, a minimum reserve margin for all time steps can be imposed. Ensuring a higher level of reliability results in an increase in cost, as one would expect, reflecting a conflict between these two objective functions. Fig. 8 captures the corresponding Pareto front for the base case with different reserve margins.

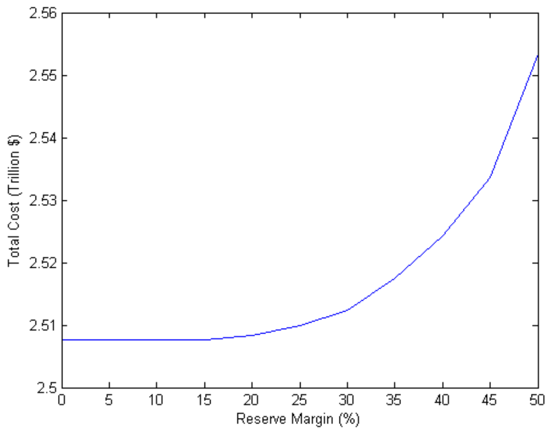

Fig. 8. Representation of non-dominated solution for two resiliency (reserve margin) and cost objectives.

Increasing reserve margin causes increasing price stability for energy. Fig. 9 shows the evolution in time of electricity prices for three different levels of reserve margin (0, 25% and 50%) for both the Midwest and the East Coast.

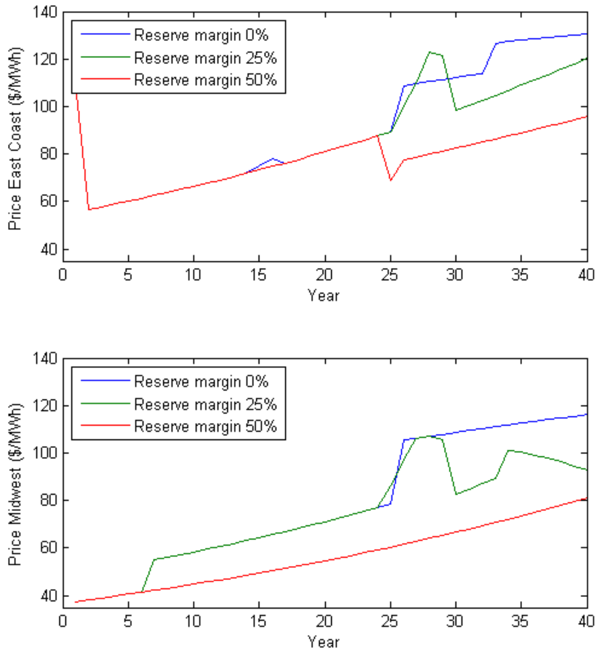

Fig. 9. Price stability and reserve margin in the two geographical regions for different levels of reserve margin.

In previous steps, operational and investment cost was studied with respect to emissions and reserve margin. Both methodologies can be combined to obtain a multiobjective approach to the problem with three objective functions: cost, emissions and reliability. Evaluating a number of combinations of minimum investment on wind generation and minimum reserve margin, we obtain the Pareto surface pictured in Fig. 10, corresponding to the solutions to the multiobjective problem.

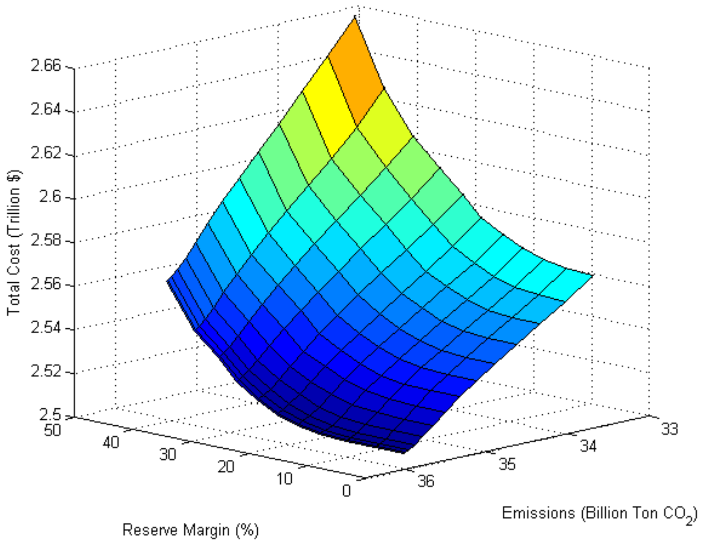

Fig. 10. Pareto surface of non-dominated solutions in terms of cost, sustainability (CO_2 emissions) and resiliency (reserve margin).

8 Discussion

A new approach to assess investment on national energy and transportation infrastructures has been presented in this chapter. It features a multiobjective approach, enabling the optimization on cost, sustainability and resiliency. A formulation has been developed, which allows the implementation of such a model for minimization of cost and emissions.

The formulation has been applied to a simple example representing the Midwestern and Eastern sections of the United States. Even though it has been represented at a very high level, the order of magnitude of the results in terms of costs, emissions and energy prices agrees with those in the real operation of the energy and transportation systems [1,59]. The model forecasts an average operation expenditure of $58 billion per year with an average emission of 893 million tons of CO_2/year, which is consistent with DOE estimates. Electricity prices are also reasonable within markets today.

The model allows the study of some of the interdependencies presented in the chapter. The most interesting one relates the cost of electricity with the operation in the transportation system. If transportation of coal and corn creates a congested rail connection, electricity prices increase as more corn must be shipped by the higher-price truck in order to allow more coal to be shipped by rail. We could think of this situation as an extension of the idea of locational marginal price, the price is set by the cost of supplying the next unit of energy. To produce one more MWh of electricity, more coal is needed to be transported but the rail is congested. The solution is to transfer part of the corn by truck to enable the shipment of the extra coal. Therefore, the price of energy suffers a significant increase.

An initial attempt for multiobjective calculations has been introduced in the example, both in terms on emissions and reliability. Pareto fronts of solutions have been calculated and plotted, which enable the study of trade-off between different solutions. New metrics to compute sustainability and resiliency need to be develop to further in this type of calculations.

The example presented here is meaningful, but has been severely restricted in dimensionality in order to illustrate the approach. This methodology can be expanded by introducing new geographical regions interconnected with more arcs, and new energy and transportation networks with a wider range of technologies, transportation infrastructures and fleets, either readily available or coming in the future.

The methodology presented in this chapter, when applied over a full scale representation of the national energy and transportation systems could be used as an assessment tool for decision makers and the general public to debate on the future of these infrastructures. Federal agencies, states and a wide spectrum of private companies could benefit from the comprehensive analysis in order to establish the appropriate balance among the best alternatives in terms of cost, sustainability and resiliency.

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